

ABOUT R -PARITY AND THE SUPERSYMMETRIC STANDARD MODEL

P. FAYET

*Laboratoire de Physique Théorique de l'Ecole Normale Supérieure^a,
24 rue Lhomond, 75231 Paris Cedex 05, France,
E-mail: fayet@physique.ens.fr*

We recall the obstacles which seemed, long ago, to prevent one from viewing supersymmetry as a possible fundamental symmetry of Nature. Is spontaneous supersymmetry breaking possible? Where is the spin- $\frac{1}{2}$ Goldstone fermion of supersymmetry, if not a neutrino? Which bosons and fermions could be related? Can one define conserved baryon and lepton numbers in such theories, although they systematically involve self-conjugate Majorana fermions? If we have to postulate the existence of new bosons carrying B and L (the new spin-0 squarks and sleptons), can we prevent them from mediating new unwanted interactions?

We then recall how we obtained the three basic ingredients of the Supersymmetric Standard Model: 1) the $SU(3) \times SU(2) \times U(1)$ gauge superfields; 2) the chiral quark and lepton superfields; 3) the two doublet Higgs superfields responsible for the electroweak breaking, and the generation of quark and lepton masses. The original continuous “ R -invariance” of this model was soon abandoned in favor of its discrete version, R -parity, so that the gravitino, and gluinos, can acquire masses – gluinos getting their masses from supergravity, or radiative corrections.

R -parity forbids unwanted squark and slepton exchanges, and guarantees the stability of the “lightest supersymmetric particle”. It is present only since we restricted the initial superpotential to be an *even* function of quark and lepton superfields (so as to allow for B and L conservation laws), as made apparent by the formula re-expressing R -parity as $(-1)^{2S} (-1)^{(3B+L)}$. Whether it turns out to be absolutely conserved, or not, R -parity plays an essential rôle in the phenomenology of supersymmetric theories, and the experimental searches for the new particles.

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1 Introduction

The algebraic structure of supersymmetry in four dimensions, introduced in the beginning of the seventies by Gol’fand and Likhtman¹, Volkov and Akulov², and Wess and Zumino³, involves a spin- $\frac{1}{2}$ fermionic symmetry generator Q satisfying the (anti) commutation relations:

$$\left\{ \begin{array}{l} \{ Q, \bar{Q} \} = -2 \gamma_\mu P^\mu \quad , \\ [Q, P^\mu] = 0 \quad . \end{array} \right. \quad (1)$$

This (Majorana) spin- $\frac{1}{2}$ supersymmetry generator Q was originally introduced as relating fermionic with bosonic fields, in the framework of relativistic field theories. It can potentially relate fermions and bosons in a physical theory, provided one succeeds in identifying physical fermions and bosons that might be related under such a symmetry. The presence of the generator of spacetime translations P^μ in the right-handside of the anticommutation relations (1) is at the origin of the relation of supersymmetry with general relativity and gravitation, since a locally supersymmetric theory must be invariant under local coordinate transformations.

The consideration of this algebraic structure, if it is to be taken seriously as a possible symmetry of the physics of fundamental particles and interactions, led us to postulate the existence of new “superpartners” for all ordinary particles^{4,5}. These still-hypothetical superpartners may be attributed a new quantum number called R -parity, which may be multiplicatively conserved in a natural way, and is especially useful to guarantee the absence of unwanted interactions mediated by squark or slepton exchanges, that might otherwise be present. As is well-known, the conservation (or non-conservation) of R -parity is closely related with the conservation (or non-conservation) of baryon and lepton numbers, B and L . A conserved R -parity also ensures the stability of the “lightest supersymmetric particle”, a good candidate to constitute a part of the Dark Matter that seems to be present in our Universe.

It may be worth to go back in time, and think a little bit more about supersymmetry, and the way it might be present in Nature. The supersymmetry algebra (1) was introduced, in the years 1971-1973, by three different groups, with quite different motivations. Gol’fand and Likhtman¹, in their remarkable work published in 1971, first introduced it in connection with parity-violation, presumably in view of understanding parity-violation in weak interactions: when the Majorana supersymmetry generator Q_α is written as a two-component chiral Dirac spinor (e.g. Q_L), one may have the impression

that the supersymmetry algebra is intrinsically parity-violating (which, however, is not the case). Volkov and Akulov² hoped to explain the masslessness of the neutrino from a possible interpretation as a spin- $\frac{1}{2}$ Goldstone particle, while Wess and Zumino³ wrote the algebra by extending to four dimensions the “supergauge” (i.e. supersymmetry) transformations⁶, and algebra⁷, acting on the two-dimensional string worldsheet.

The mathematical existence of an algebraic structure does not imply that it has to play a rôle as an invariance of the fundamental laws of Nature. Incidentally while supersymmetry is commonly referred to as “relating fermions with bosons”, its algebra (1) does not even require the existence of fundamental bosons (and even less of the superpartners that were introduced later)! With non-linear realizations of supersymmetry a fermionic field can be transformed into a *composite* bosonic field made of fermionic ones². Still we shall concentrate on the framework of the “linear realizations” of the supersymmetry algebra, which seems to be the most promising one, so as to work within the context of renormalizable supersymmetric gauge theories (as far as weak, electromagnetic and strong interactions are concerned).

2 Nature does not seem to supersymmetric !

Could supersymmetry be present as a fundamental symmetry of Nature, or is it doomed to remain, as it initially seemed for some time, as a mathematical algebraic structure, only? Can we use this symmetry to relate directly known bosons and fermions? And, if not, why? If known bosons and fermions cannot be directly related by supersymmetry, do we have to accept this as the sign that supersymmetry is *not* a symmetry of the fundamental laws of Nature, and drop this apparently unsuccessful idea? Indeed, in the early days of supersymmetry (around 1974 or so), many obstacles seemed to make its physical realization impossible.

Some of the main obstacles are summarized by the following questions (Q i’s) below. The most obvious one comes from the fact that, while bosons and fermions should have equal masses in a supersymmetric theory (in the framework of the “linear realizations” of the supersymmetry algebra), this is obviously not the case in Nature. Supersymmetry should then clearly be broken. At first sight this does not necessarily seem to be a problem, since we are so used to deal with spontaneously broken symmetries, such as, in particular, spontaneously broken gauge theories.

But supersymmetry is a special symmetry, since the Hamiltonian – which plays an essential rôle in the definition of a stable vacuum state with minimum energy – appears in the right-handside of the anticommutation relations (1) of the supersymmetry algebra. Actually this Hamiltonian can be expressed proportionally to the sum of the squares of the components of the supersymmetry generator, $H = \frac{1}{4} \sum_{\alpha} Q_{\alpha}^2$. This shows that a supersymmetry-preserving vacuum state must have vanishing energy⁸, while a state which is not invariant under supersymmetry could naïvely be expected to have a larger, positive, energy. Indeed, such a supersymmetry-breaking state actually corresponds, in global supersymmetry, to a positive energy density, the scalar potential, written proportionally to the sum of the squares of the auxiliary D , F and G components as $V = \frac{1}{2} \sum (D^2 + F^2 + G^2)$, being strictly positive. As a result, potential candidates for supersymmetry-breaking vacuum states seemed to be necessarily unstable, with some of the spin-0 particles having negative mass², which is evidently not acceptable! This initially seemed to make spontaneous supersymmetry-breaking impossible, leading to the question:

Q1 :

Is spontaneous supersymmetry-breaking possible at all?

As we know several ways of breaking spontaneously global or local supersymmetry have been found^{9,10,11}. But spontaneous supersymmetry-breaking remains, in general, rather difficult to obtain, since theories tend to prefer, for energy reasons, supersymmetric vacuum states. Then, how can spontaneous supersymmetry-breaking be possible?

As we said above in global supersymmetry a non-supersymmetric state has, in principle, always more energy than a supersymmetric one, whose energy vanishes identically; it then seems that it should be unstable, the stable vacuum state being, necessarily, a supersymmetric one! Still it is possible to escape this general result – and this is the key to supersymmetry-breaking – if one can arrange to be in one of those rare situations for which *no supersymmetric state exists at all* – the set of equations $\langle D \rangle' s = \langle F \rangle' s = \langle G \rangle' s = 0$ having *no solution at all*. But these situations are in general quite exceptional. (This is in sharp contrast with ordinary gauge theories, for which one only has to arrange for non-symmetric states to have less energy than symmetric ones, in order to get spontaneous symmetry-breaking.)

These rare situations usually involve an abelian $U(1)$ gauge group⁹, allowing for a gauge-invariant linear “ ξD ” term to be included in the Lagrangian

density^b; and/or an appropriate set of chiral superfields with very carefully chosen superpotential interactions (“ F -breaking”) ¹⁰. In local supersymmetry ¹², which includes gravity, one has to arrange, at the price of a very severe fine-tuning, for the energy density of the vacuum to vanish exactly ¹¹, or almost exactly, to an extremely good accuracy, so as not to generate an unacceptably large value of the cosmological constant Λ .

Once we know that it is possible to break supersymmetry spontaneously, we shall still have to break it in an acceptable way, so as to get – if this is indeed possible – a physical world which looks like the one we know! (The above $U(1)$ ⁹, in particular, *cannot* be identified with the weak hypercharge $U(1)$ of a physically-meaningful theory ¹³, but might have been, instead, a new “extra $U(1)$ ” gauge symmetry ⁴.) Of course just accepting explicit supersymmetry-breaking without worrying too much about the origin of supersymmetry-breaking terms would make things much easier – also at the price of introducing a large number of arbitrary parameters, coefficients of these supersymmetry-breaking terms. But such terms must have their origin in a spontaneous supersymmetry-breaking mechanism, if we want supersymmetry to play a fundamental role, especially if it is to be realized as a local fermionic gauge symmetry, as in the framework of supergravity theories.

Another question to be asked immediately after learning that spontaneous supersymmetry breaking is indeed possible, is:

Q2 : Where is the spin- $\frac{1}{2}$ Goldstone fermion of supersymmetry ?

The spontaneous breaking of the global supersymmetry must generate a massless spin- $\frac{1}{2}$ Goldstone particle. Could it be one of the known neutrinos ²? A first attempt at implementing the idea within a $SU(2) \times U(1)$ electroweak model of “leptons” ¹⁴ (of the “electron” sector), discussed later in section 3, quickly illustrated that this idea could not be pursued very far, for many reasons: the existence of several neutrinos (two were known at that time), the fact that attributing a Goldstone rôle to one of them (and which one?) would break the lepton/quark universality, the fact that a Goldstone particle

^bEven in the presence of such a term, one does not necessarily get a spontaneous breaking of the supersymmetry: one has to be very careful so as to avoid the presence of supersymmetry-restoring vacuum states, which generally tend to exist. In a physical theory, whatever is the mechanism of supersymmetry breaking considered, one will have to check carefully, in particular, for the non-existence of stable vacuum states for which electric charge and/or color symmetry would be spontaneously broken.

has couplings of a very particular type which have to do with the boson-fermion mass-splittings (or mass²-splittings) within the multiplets of supersymmetry^{14,5} (couplings from which one cannot recover those of a neutrino), lepton-number conservation, low-energy theorems¹⁵, etc..

So, if the Goldstone fermion associated with the spontaneous breaking of the global supersymmetry is not one of the known neutrinos, where is it, and why hasn't it been observed? One might suggest that it could be an (almost-decoupled) right-handed neutrino ν_R , but, again, the idea cannot be pursued very seriously, very much for the same reasons that we just indicated.

So, where is the spin- $\frac{1}{2}$ Goldstone fermion of supersymmetry? Today we tend not to think at all about the question, since: 1) the use of soft terms breaking *explicitly* the supersymmetry makes the question irrelevant; 2) since supersymmetry has to be realized locally anyway, within the framework of supergravity¹², the massless spin- $\frac{1}{2}$ Goldstone fermion ("goldstino") should in any case be eliminated in favor of extra degrees of freedom for a massive spin- $\frac{3}{2}$ gravitino^{5,11}. So there is no goldstino, but a massive gravitino instead.

But the same question now gets transformed into: where is the gravitino, and why has no one either seen a fundamental spin- $\frac{3}{2}$ particle? To discuss it properly we need to know how bosons and fermions could be associated under supersymmetry (cf. the subsequent question Q3). But we can anticipate that the interactions of the gravitino, being proportional to the Newton constant $G_N \simeq 10^{-38} \text{ GeV}^{-2}$, should be absolutely negligible in particle physics experiments, so that this particle, even if it could be produced, would in any case remain undetected. This should indeed be true, if the gravitino is heavy.

However we might be in a situation for which the gravitino is light, maybe even extremely light, so that it would still interact very much like the massless Goldstone fermion of spontaneously-broken global supersymmetry, according to the "equivalence theorem" of supersymmetry⁵. In that case, the gravitino could well have non-negligible interactions, relevant in particle physics, so that we should ask again the same question, but now for the $\pm\frac{1}{2}$ polarization states of the massive spin- $\frac{3}{2}$ gravitino. The answer may be given later, after we get to the Supersymmetric Standard Model (cf. sections 4 and 5): if R -parity is conserved, the R -odd gravitino should be produced in association with another R -odd superpartner – but it now seems that these superpartners should all be rather heavy. (One may also consider the pair-production of very light gravitinos, but it is normally strongly suppressed at lower energies.)

Leaving for the moment this question of supersymmetry breaking, the next – and equally obvious – question to be asked after questions Q1 and Q2, is

Q3 : Which bosons and fermions could be related by supersymmetry ?

There seems to be no positive answer to this question since the bosons and fermions that we know do not seem to have much in common – excepted maybe for the photon and the neutrino, which are both electrically neutral and massless (or almost massless). We shall come back to this point in section 3.

Furthermore, from a more general point of view, the number of (known) fermionic degrees of freedom is significantly larger than for bosonic ones. Actually we know today six quarks and six leptons, corresponding with their antiparticles to 90 fermionic degrees of freedom. On the other hand the bosons that we know for sure to exist (ignoring the spin-2 graviton and the still-undiscovered Higgs boson) are the color-octet of gluons, the photon, and the W^\pm and Z gauge bosons, which altogether correspond to 27 degrees of freedom, only. In addition, these fermions and bosons have different gauge symmetry properties, e.g. the spin- $\frac{1}{2}$ quarks are (charged) color triplets while the spin-1 gluons form a (neutral) color octet (so that attempting to relate directly gluons with quarks, for example, would necessitate extended supersymmetry generators carrying both color and charge, requiring very large representations involving higher-spin fields).

Another question, to which we shall return in sections 4 to 6, is the question of the definition of conserved baryon and lepton numbers. It once appeared as a serious difficulty in supersymmetric theories, especially since they systematically involve self-conjugate Majorana spinors:

Q4 : How could one define conserved
baryon and lepton numbers, in a supersymmetric theory ?

Indeed these quantum numbers are known (for the moment) to be *carried by fermions only* (the familiar spin- $\frac{1}{2}$ quarks and leptons), and *not* by bosons. If we do insist on this property there is no real hope to be able to define such conserved baryonic and leptonic numbers ! (Of course nowadays we are so used to deal with spin-0 quarks and leptons, carrying baryon and lepton numbers almost by definition, that we can hardly imagine this could once have appeared as a problem.)

The solution to the problem went through the acceptance of the idea of introducing a large number of new bosons, also carrying baryon and lepton numbers, despite the fact that B and L were then viewed as intrinsically-fermionic numbers. One had to accept the new idea of having **baryon and lepton numbers also carried by bosons!**

But if new spin-0 bosons carrying baryon or lepton numbers are introduced (i.e. the new spin-0 quarks and leptons), their direct (Yukawa) exchanges between ordinary spin- $\frac{1}{2}$ quarks and leptons, if allowed, could lead to an immediate disaster, preventing us from getting a theory of weak, electromagnetic and strong interactions mediated by spin-1 gauge bosons (and not spin-0 particles), with conserved B and L quantum numbers!

Q5 :

How can we avoid unwanted interactions mediated by spin-0 squark and slepton exchanges?

Fortunately, we can naturally avoid the existence of such unwanted interactions, thanks to R -parity, which guarantees that squarks and sleptons *cannot* be directly exchanged between ordinary quarks and leptons, allowing for conserved baryon and lepton numbers in supersymmetric theories.

3 R -invariance and electroweak breaking, from an attempt to relate the photon with the neutrino.

Let us now return to an early attempt at relating *existing* bosons and fermions together. Despite the general lack of similarities between known bosons and fermions, we might still try as an exercise to see how far one could go in attempting to relate the photon with one of the neutrinos (say “ ν_e ”), in the framework of a spontaneously-broken supersymmetric theory¹⁴. At the same time, the W^- boson could be related with a would-be “electron”. This early model also showed how it was possible to define a conserved “leptonic” number – called R . At that time the definition of a conserved quantum number carried by Dirac fermions posed a rather severe problem in supersymmetric theories, since these theories make an extensive use of Majorana spinors, e.g. the spin- $\frac{1}{2}$ partners of the spin-1 gauge bosons, now called “gauginos”. In particular the fermionic partner of the photon – to be called later the photino – is precisely described by such a *self-conjugate* Majorana spinor.

If we want to try to identify this companion of the photon as being a “neutrino”, we need to understand how it could carry a conserved quantum number that we could interpret as a “lepton” number. We also need to be able to reconstruct charged massive Dirac spinors from originally massless components, having, furthermore, different electroweak gauge symmetry properties.

In the case of this toy $SU(2) \times U(1)$ model of “leptons”, the solution is obtained through the definition of

$$a \text{ continuous } U(1) \text{ } R\text{-invariance,}$$

which made it possible to define such a conserved “leptonic” number. It had the property that one unit of this – additive – quantum number (called R !) was carried by the supersymmetry generator Q_α . The “electron” and “neutrino” candidates were indeed described by massive and massless Dirac spinors, each of them carrying one unit of the conserved quantum number R . This continuous $U(1)$ R -invariance¹⁴, which also guaranteed the masslessness of the “neutrino”, acted chirally on the Grassmann coordinate θ which appears in the expression of the various (gauge and chiral) superfields.

In this first attempt – which essentially became later a part of the Supersymmetric Standard Model – Higgs doublets responsible for the electroweak breaking were related with “leptonic” doublets under supersymmetry. But in the resulting model (which also included a “heavy electron” carrying -1 unit of the additive R quantum number) one chiral component of the charged “electron” field transformed as the lower member of an $SU(2)$ triplet (and the other as the lower member of a doublet)^c, and the “neutrino” was not directly coupled to the Z boson. As we know now, this is not acceptable (nor is it for the leptons of the two other families, the one of the muon and the one of the τ^-). Furthermore, if we insisted on such a scheme for the leptons of the electron sector, what should we do with the other leptons of the muon and τ sectors, and with the quarks?

It was clear from the beginning that attempting to relate the photon with one of the neutrinos could only be an exercise of limited validity, but it had the merit of illustrating how one can break spontaneously a $SU(2) \times U(1)$ gauge symmetry in a supersymmetric theory, through an electroweak breaking induced by

^cThis would-be “electron” was obtained from a charged left-handed “gaugino” field (\tilde{W}_L^-), which acquired a mass by combining with a charged right-handed “higgsino” field. The “neutrino” was then described by the left-handed gaugino field $\tilde{\gamma}_L$.

a pair of chiral doublet Higgs superfields,

now known as H_1 and H_2 (or H and \bar{H}). In modern language, our previous would-be “electron” and “heavy electron” were in fact what we now call two winos, or charginos, obtained through a mixing of charged gaugino and higgsino components. The associated mass matrix simply reads, in a gaugino/higgsino basis,

$$\mathcal{M} = \begin{pmatrix} (m_2 = 0) & \frac{g v_2}{\sqrt{2}} = m_W \sqrt{2} \sin \beta \\ \frac{g v_1}{\sqrt{2}} = m_W \sqrt{2} \cos \beta & \mu = 0 \end{pmatrix}, \quad (2)$$

in the absence of a direct higgsino mass originating from a $\mu H_1 H_2$ mass term in the superpotential. This μ term, which would have broken explicitly the continuous $U(1)$ R -invariance intended to be associated with the “lepton” number conservation law, was already replaced by a $\lambda H_1 H_2 N$ trilinear coupling involving an *extra neutral singlet chiral superfield* N ^d:

$$\mu H_1 H_2 \quad \longmapsto \quad \lambda H_1 H_2 N. \quad (3)$$

Let us note in passing that using only *one* doublet Higgs superfield H , describing a single *chiral* higgsino doublet, which would now be denoted as, e.g. $\begin{pmatrix} \tilde{h}^0 \\ \tilde{h}^- \end{pmatrix}_L$, would have led to “one and a half” charged Dirac fermion, namely a charged Dirac “gaugino” (\tilde{W}^-) mixed with a *chiral* charged Dirac “higgsino” (\tilde{h}_L^-), leaving us with a massless charged chiral fermion. This would be, evidently, unacceptable (even before having to take into consideration the corresponding anomalies, that would then be present, already, in the quantum theory of *electromagnetism*).

The whole construction showed that one could deal elegantly with spin-0 Higgs boson fields (not a very popular ingredient at the time) in the framework of spontaneously-broken supersymmetric theories. Quartic Higgs couplings are no longer completely arbitrary, but get fixed by the values of the gauge coupling

^dA gaugino mass term parametrized, in the case of $SU(2)$, by m_2 , which would also have violated the continuous $U(1)$ R -invariance (in addition to the supersymmetry), does not appear, at tree level, in global supersymmetry. But it could be generated by radiative corrections, as soon as the continuous R -invariance is no longer present; it is also allowed in spontaneously-broken *locally* supersymmetric theories, as we shall discuss in section 7.

constants – g and g' – through the following “ D -terms” (i.e. $\frac{\bar{D}^2}{2} + \frac{D'^2}{2}$) in the scalar potential given in ¹⁴ (with a different denomination for the two Higgs doublets, such that $\varphi'' \mapsto h_1$, $(\varphi')^c \mapsto h_2$, $\tan \delta = v'/v'' \mapsto \tan \beta = v_2/v_1$):

$$\begin{aligned} V_{\text{Higgs}} &= \frac{g^2}{8} (h_1^\dagger \tilde{\tau} h_1 + h_2^\dagger \tilde{\tau} h_2)^2 + \frac{g'^2}{8} (h_1^\dagger h_1 - h_2^\dagger h_2)^2 + \dots \\ &= \frac{g^2 + g'^2}{8} (h_1^\dagger h_1 - h_2^\dagger h_2)^2 + \frac{g^2}{2} |h_1^\dagger h_2|^2 + \dots \end{aligned} \quad (4)$$

This is precisely the quartic Higgs potential of the “minimal” version of the Supersymmetric Standard Model, the so-called MSSM, with its quartic Higgs coupling constants equal to

$$\frac{g^2 + g'^2}{8} \quad \text{and} \quad \frac{g^2}{2} . \quad (5)$$

Further contributions to this quartic Higgs potential also appear in the presence of additional superfields, such as the neutral singlet chiral superfield N already introduced in this model, which will play an important rôle in the NMSSM, i.e. in “next-to-minimal” or “non-minimal” versions of the Supersymmetric Standard Model.

Charged Higgs bosons (now called H^\pm) are present in this framework, as well as *several neutral ones*. All this is at the origin of various mass relations (equalities or inequalities) connecting Higgs masses to gauge boson masses in supersymmetric theories. Their particular expressions depend on the details of the supersymmetry-breaking mechanism considered: soft-breaking terms, possibly “derived from supergravity”, presence or absence of extra- $U(1)$ gauge fields and/or additional chiral superfields, use of radiative corrections, etc..

4 From the electroweak breaking to the Supersymmetric Standard Model.

These two Higgs doublets H_1 and H_2 are precisely the two doublets which I used in 1977 to generate the masses of charged-leptons and down-quarks, and of up-quarks, in supersymmetric extensions of the standard model ⁴. Note that at the time having to introduce Higgs fields was generally considered as rather unpleasant, at least. While one Higgs doublet was taken as probably unavoidable to get to the standard model or in any case simulate the effects of

the spontaneous breaking of the electroweak symmetry, having to consider two Higgs doublets, thereby necessitating charged Higgs bosons as well as several neutral ones, was usually considered as a too heavy price, in addition to the “doubling of the number of particles”, once considered as an indication of the irrelevance of supersymmetry. Actually many physicists spent a lot of time, later on, trying to avoid fundamental spin-0 Higgs fields and particles, before returning to fundamental Higgses, precisely in this framework of supersymmetry.

In the previous $SU(2) \times U(1)$ model¹⁴, it was clearly impossible to view seriously for very long “gaugino” and “higgsino” fields as possible building blocks for our familiar lepton fields. This becomes even more patent if one takes again quarks and gluons into consideration. This led us to consider that all quarks, and leptons as well, should be associated with new bosonic partners, the **spin-0 quarks and leptons**. Gauginos and higgsinos, mixed together by the spontaneous breaking of the electroweak symmetry, correspond to a new class of fermions, now known as “charginos” and “neutralinos”.

In particular, the partner of the photon under supersymmetry, which cannot be identified with any of the known neutrinos, should be viewed as a new “photonic neutrino” which I called in 1977 the **photino**; the fermionic partner of the gluon octet is an octet of self-conjugate Majorana fermions called **gluinos**, etc. – although at the time *colored fermions* belonging to *octet* representations of the color $SU(3)$ gauge group were generally believed not to exist^e!

The two doublet Higgs superfields H_1 and H_2 introduced previously are precisely those needed to generate quark and lepton masses in supersymmetric extensions of the standard model^{4 f}, in the now-usual way, through the familiar trilinear superpotential

$$\mathcal{W} = h_e H_1 \cdot \bar{E} L + h_d H_1 \cdot \bar{D} Q - h_u H_2 \cdot \bar{U} Q \quad . \quad (6)$$

Here L and Q denote the left-handed doublet lepton and quark superfields, and \bar{E} , \bar{D} and \bar{U} left-handed singlet antilepton and antiquark superfields. (We originally denoted, generically, by S_i , left-handed, and T_j , right-handed, the chiral superfields describing the left-handed and right-handed spin- $\frac{1}{2}$ quark

^eOne could even think of using the absence of such particles as a general constraint to select admissible grand-unified theories¹⁶.

^f The correspondance between our earlier notations for doublet Higgs superfields and mixing angle, and modern ones, is as follows:

Table 1: The basic ingredients of the Supersymmetric Standard Model.

1) the three $SU(3) \times SU(2) \times U(1)$ gauge superfield representations;
2) the chiral quark and lepton superfields corresponding to the three quark and lepton families;
3) the two doublet Higgs superfields H_1 and H_2 responsible for the spontaneous electroweak symmetry breaking, and the generation of quark and lepton masses through the trilinear superpotential (6).

and lepton fields, together with their spin-0 partners.) The vacuum expectation values of the two Higgs doublets described by H_1 and H_2 generate charged-lepton and down-quark masses, and up-quark masses, given by $m_e = h_e v_1/2$, $m_d = h_d v_1/2$, and $m_u = h_u v_2/2$, respectively.

This constitutes the basic structure of the **Supersymmetric Standard Model**, which involves, at least, the basic ingredients shown in Table 1. Other ingredients, such as a direct $\mu H_1 H_2$ direct mass term in the superpotential, or an extra singlet chiral superfield N with a trilinear superpotential coupling $\lambda H_1 H_2 N + \dots$ possibly acting as a replacement for a direct $\mu H_1 H_2$ mass term, as in ¹⁴, and/or extra $U(1)$ factors in the gauge group, may or may not be present, depending on the particular version of the Supersymmetric Standard Model considered.

It is often useful to know, in addition, that the gauge interactions of the quark, lepton and Higgs superfields, and the trilinear superpotential interac-

$S = \begin{pmatrix} S^0 \\ S^- \end{pmatrix} \text{ and } T = \begin{pmatrix} T^0 \\ T^- \end{pmatrix}$ <p>(left-handed) (right-handed)</p>	$\mapsto H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \text{ and } H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$ <p>(both left-handed)</p>
$\tan \delta = \frac{\langle T^0 \rangle}{\langle S^0 \rangle} = \frac{\langle \varphi'^0 \rangle}{\langle \varphi''^0 \rangle} = \frac{v'}{v''} \mapsto \tan \beta = \frac{\langle H_2^0 \rangle}{\langle H_1^0 \rangle} = \frac{\langle h_2^0 \rangle}{\langle h_1^0 \rangle} = \frac{v_2}{v_1}$	

tions (6) responsible for quark and charged-lepton masses are also invariant under an *extra* $U(1)$ *symmetry*⁹, acting as follows:

$$\left\{ \begin{array}{ll} V(x, \theta, \bar{\theta}) \rightarrow V(x, \theta, \bar{\theta}) & \text{for the } SU(3) \times SU(2) \times U(1) \text{ gauge superfields;} \\ H_{1,2}(x, \theta) \rightarrow e^{-i\alpha} H_{1,2}(x, \theta) & \text{for the left-handed doublet Higgs superfields} \\ & H_1 \text{ and } H_2; \\ S(x, \theta) \rightarrow e^{i\frac{\alpha}{2}} S(x, \theta) & \text{for the left-handed (anti)quark and (anti)lepton} \\ & \text{superfields } Q, \bar{U}, \bar{D}, L, \bar{E}. \end{array} \right. \quad (7)$$

But a direct Higgs superfield mass term $\mu H_1 H_2$ in the superpotential is *not* invariant under this extra $U(1)$ symmetry – nor is it under the continuous $U(1)$ R -invariance discussed in the previous and following sections. Such a term, however, will get re-allowed, as soon as we shall abandon the extra $U(1)$ symmetry (given that no new neutral gauge boson or neutral-current interaction has been found), and the continuous $U(1)$ R -invariance (given that the gravitino and gluinos must be massive, as we shall discuss in section 7). The size of this “supersymmetric” μ parameter may be naturally controlled by using either the (broken) “extra- $U(1)$ ” symmetry (7), or the continuous R -invariance, that must be broken at the same time as the supersymmetry.

In any case, independently of the details of the supersymmetry-breaking mechanism ultimately going to be considered, we obtain the following minimal particle content of the Supersymmetric Standard Model, given in Table 2. Each spin- $\frac{1}{2}$ quark q or charged lepton l^- is associated with *two* spin-0 partners collectively denoted by \tilde{q} or \tilde{l}^- , while a left-handed neutrino ν_L is associated with a *single* spin-0 sneutrino $\tilde{\nu}$. We have ignored for simplicity further mixings between the various “neutralinos” described by neutral gaugino and higgsino fields, denoted in this Table by $\tilde{\gamma}$, $\tilde{Z}_{1,2}$, and \tilde{h}^0 . More precisely, all such models include 4 neutral Majorana fermions at least, corresponding to mixings of the fermionic partners of the two neutral $SU(2) \times U(1)$ gauge bosons (usually denoted by $\tilde{\gamma}$ and \tilde{Z} , or \tilde{W}_3 and \tilde{B}) and of the two neutral higgsino components (\tilde{h}_1^0 and \tilde{h}_2^0). Non-minimal models also involve

⁹This is precisely the extra $U(1)$ symmetry which we initially proposed to gauge⁴, in addition to $SU(3) \times SU(2) \times U(1)$, in order to obtain a spontaneous breaking of the global supersymmetry, and generate large tree-level masses for all squarks and sleptons. But the remaining unbroken continuous R -invariance discussed in the next section left us with massless gluinos, and the need, later on, to generate a gluino mass either from radiative corrections, or from supergravity. In both cases the continuous R -invariance is reduced to its discrete Z_2 subgroup generated by the R -parity transformation, as we shall discuss in sections 5 and 7.

Table 2: Minimal particle content of the Supersymmetric Standard Model.

Spin 1	Spin 1/2	Spin 0
gluons g photon γ	gluinos \tilde{g} photino $\tilde{\gamma}$	
W^\pm Z	winos $\tilde{W}_{1,2}^\pm$ zinos $\tilde{Z}_{1,2}$ higgsino \tilde{h}^0	H^\pm H h, A } Higgs bosons
	leptons l quarks q	sleptons \tilde{l} squarks \tilde{q}

additional gauginos^{*h*} and/or higgsinos.

5 R -invariance and R -parity in the Supersymmetric Standard Model.

As we explained earlier, the early two-Higgs-doublet $SU(2) \times U(1)$ model of 1974¹⁴ showed how one could introduce a new R quantum number, then defined as an *additive* quantum number (corresponding to a continuous $U(1)$ R -invariance) carried by the supersymmetry generator, and distinguishing between bosons and fermions inside the multiplets of supersymmetry. Gauge bosons and Higgs bosons have $R = 0$ while their partners under supersymmetry, now to be interpreted as gauginos and higgsinos (rather than lepton field candidates), have $R = \pm 1$. The definition of this continuous R -invariance was then extended to the chiral quark and lepton superfields, spin- $\frac{1}{2}$ quarks and leptons having $R = 0$, and their spin-0 superpartners, $R = +1$ (for \tilde{q}_L, \tilde{l}_L) or $R = -1$ (for \tilde{q}_R, \tilde{l}_R)⁴. The action of these continuous $U(1)$ R -symmetry transformations, which survive the spontaneous breaking of the electroweak symmetry, is given in Table 3.

^{*h*}If an extra $U(1)$ is gauged, one of the neutral Higgs bosons becomes an “eaten” Goldstone boson, while the corresponding extra- $U(1)$ neutral gauge boson (called Z' or U) acquires a mass.

Table 3: Action of a continuous $U(1)$ R -symmetry transformation on the gauge and chiral superfields of the Supersymmetric Standard Model.

$V(x, \theta, \bar{\theta}) \rightarrow V(x, \theta e^{-i\alpha}, \bar{\theta} e^{i\alpha})$	for the $SU(3) \times SU(2) \times U(1)$ gauge superfields
$H_{1,2}(x, \theta) \rightarrow H_{1,2}(x, \theta e^{-i\alpha})$	for the two left-handed chiral doublet Higgs superfields H_1 and H_2
$S(x, \theta) \rightarrow e^{i\alpha} S(x, \theta e^{-i\alpha})$	for the left-handed chiral (anti)quark and lepton superfields $Q, \bar{U}, \bar{D}, L, \bar{E}$

The $SU(3) \times SU(2) \times U(1)$ gauge interactions of the chiral quark and lepton superfields, and of the two doublet Higgs superfields H_1 and H_2 , are indeed invariant under this continuous $U(1)$ R -symmetry. So are the super-Yukawa interactions of the two doublet Higgs superfields H_1 and H_2 responsible for the generation of quark and lepton masses through the superpotential (6). Indeed this trilinear superpotential transforms under continuous R -symmetry with “ R -weight” $n_{\mathcal{W}} = \sum_i n_i = 2$, i.e. according to

$$\mathcal{W}(x, \theta) \rightarrow e^{2i\alpha} \mathcal{W}(x, \theta e^{-i\alpha}) . \quad (8)$$

Its auxiliary “ F -component” is therefore R -invariant, and generates R -invariant interaction terms in the Lagrangian density.

This R -invariance led us to distinguish between a sector of *R -even particles*, which includes all the ordinary particles of the standard model, gauge and Higgs bosons, leptons and quarks, with $R = 0$; and their *R -odd superpartners*, gauginos and higgsinos, and spin-0 leptons and quarks, with $R = \pm 1$, as indicated in Table 4.

More precisely the necessity of generating masses for the (Majorana) spin- $\frac{3}{2}$ gravitino⁵, and for the spin- $\frac{1}{2}$ gluinos, as we shall discuss later in section 7, did not allow us to keep the distinction between $R = +1$ and $R = -1$ particles, forcing us to abandon the continuous R -invariance in favor of its discrete version, R -parity. The – even or odd – parity character of the (additive) R quantum number corresponds to the well-known **R -parity**, first defined as

Table 4: R -parities in the Supersymmetric Standard Model.

Bosons	Fermions
gauge and Higgs bosons ($R = 0$) R -parity $+$	gauginos and higgsinos ($R = \pm 1$) R -parity $-$
sleptons and squarks ($R = \pm 1$) R -parity $-$	leptons and quarks ($R = 0$) R -parity $+$

$+1$ for the ordinary particles and -1 for their superpartners, which may be written as $(-1)^R$ ¹⁷:

$$R\text{-parity } R_p = (-1)^R = \begin{cases} +1 & \text{for ordinary particles,} \\ -1 & \text{for their superpartners.} \end{cases} \quad (9)$$

6 Relation of R -parity with B and L quantum numbers.

In addition, there is a close connection between R -parity and baryon and lepton number conservation laws, which has its origin in our initial desire to obtain supersymmetric theories in which B and L could be conserved. Actually the superpotential of the theories discussed in Ref. ⁴ was constrained from the beginning, for that purpose, to be an *even* function of the quark and lepton superfields.

In other terms, *odd* superpotential terms (\mathcal{W}'), which would have violated the “matter-parity” symmetry $(-1)^{(3B+L)}$, were excluded from the beginning, to be able to recover B and L conservation laws, and at the same time avoid unwanted direct Yukawa exchanges of spin-0 quarks and leptons between ordinary spin- $\frac{1}{2}$ quarks and leptons. Tolerating unnecessary superpotential terms which are *odd* functions of the quark and lepton superfields (i.e.

R_p -violating terms, such as those which were widely discussed later), does indeed create immediate problems with baryon and lepton number conservation laws: most notably a squark-induced proton instability with a much too fast decay rate, if both B and L violations are simultaneously allowed; or neutrino masses (and other effects) that could be too large, if L -violations are allowed so that ordinary neutrinos can mix with neutral higgsinos and gauginos.

The question was raised very early, in the discussion of the phenomenology of supersymmetric theories, and the experimental searches for the gluinos and the “ R -hadrons” they could form^{18,19}, of how general is this notion of R -parity, as defined previously by eq. (9). To answer more easily it is useful to make the above connection between R -parity and B and L conservation laws more transparent. It can indeed be made quite obvious by noting that for usual particles, $(-1)^{2\text{Spin}}$ coincides with $(-1)^{3B+L}$. This immediately leads to a simple redefinition of the R -parity (9) in terms of the spin S and a “matter-parity” $(-1)^{3B+L}$, as follows¹⁸:

$$R\text{-parity} = (-1)^{2S} (-1)^{3B+L} . \quad (10)$$

This may also be rewritten as $(-1)^{2S} (-1)^{3(B-L)}$, showing that R -parity may still be conserved even if baryon and lepton numbers are separately violated (as in grand-unified theories), as long as their difference $(B - L)$ remains conserved, even only modulo 2.

This R -parity symmetry operator may also be viewed as a non-trivial geometrical discrete symmetry associated with a reflection of the anticommuting fermionic Grassmann coordinate, $\theta \rightarrow -\theta$, in superspace²⁰.

This R -parity operator plays an essential rôle in the construction of supersymmetric theories of interactions, and in the discussion of the experimental signatures of the new particles. R -invariance or simply its discrete version, a conserved R -parity, guarantees that *the new spin-0 squarks and sleptons cannot be directly exchanged* between ordinary quarks and leptons. But let us now discuss more precisely the reasons which led us to abandon the continuous R -invariance in favor of its discrete version, R -parity.

7 Gravitino and gluino masses: from R -invariance to R -parity.

There are at least two strong reasons to abandon, at some point, the continuous R -invariance, in favor of its discrete Z_2 subgroup generated by the R -parity transformationⁱ. One is theoretical, the necessity – once gravitation is introduced – of generating a mass for the (Majorana) spin- $\frac{3}{2}$ *gravitino* in the framework of spontaneously-broken locally supersymmetric theories⁵. The other is phenomenological, the non-observation of massless (or even light) *gluinos*. Both particles would have to stay massless, in the absence of a breaking of the continuous $U(1)$ R -invariance.

This is also connected with the mechanism by which the supersymmetry should get spontaneously broken, in the Supersymmetric Standard Model. The question still has not received a definitive answer yet. While we first considered in 1976 the inclusion of universal soft supersymmetry-breaking terms for all squarks and sleptons,

$$- \sum_{\tilde{q}, \tilde{l}} m_0^2 (\tilde{q}^\dagger \tilde{q} + \tilde{l}^\dagger \tilde{l}) , \quad (11)$$

such terms should in fact be generated by some spontaneous supersymmetry-breaking mechanism, if supersymmetry is to be realized locally.

Indeed they could be generated spontaneously, for example by gauging the “extra- $U(1)$ ” symmetry (7) already mentioned in section 4. This symmetry is associated, in the simplest case, with a purely axial extra- $U(1)$ current for all quarks and charged leptons. Gauging such an extra $U(1)$ is in fact necessary¹³, if one intends to generate large positive mass² for all squarks ($\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$) and sleptons, at the classical level, in a spontaneously-broken globally supersymmetric theory. But this required new neutral current interactions – unobserved – and left us with the necessity of generating, also, large gluino masses – a question to which we shall return soon. As a result, the gauging of an extra $U(1)$ no longer appears as an appropriate way to generate large superpartner masses. One now uses in general, again, soft supersymmetry-breaking terms²¹ (possibly “induced by supergravity”), which essentially serve as a parametrization of our ignorance about the true mechanism of supersymmetry breaking chosen by Nature to make superpartners heavy (if supersymmetry is indeed a symmetry of Nature!).

ⁱWe disregard other possibilities involving extended supersymmetry with a continuous $U(1)$ R -invariance, which may allow for massive *Dirac* gravitinos and gluinos, carrying one unit of a conserved, additive R quantum number.

Let us return to the question of gluino masses. Since R -transformations act *chirally* on the Majorana octet of gluinos,

$$\tilde{g} \rightarrow e^{\gamma_5 \alpha} \tilde{g} . \quad (12)$$

a continuous R -invariance would require the gluinos to remain massless, even after a spontaneous breaking of the supersymmetry! We would then expect the existence of relatively light “ R -hadrons” (bound states of quarks, anti-quarks and gluinos), which have not been observed^{18,19}. Present experimental results indicate that gluinos, if they do exist, must be very massive, requiring a significant breaking of the continuous R -invariance.

In the framework of global supersymmetry it is not so easy to generate large gluino masses. Even if global supersymmetry is spontaneously broken, and if the continuous R -symmetry is not present, it is still in general rather difficult to obtain large masses for gluinos, since²²:

- i) no direct gluino mass term is present in the supersymmetric Lagrangian density;
- ii) no gluino mass term may be generated spontaneously, at the tree approximation: gluino couplings involve *colored* spin-0 fields, which cannot be translated if the color $SU(3)$ gauge group is to remain unbroken;
- iii) a gluino mass term may then be generated by radiative corrections, but this can only be through diagrams which “know” both about:
 - a) the spontaneous breaking of the global supersymmetry, through some appropriately-generated $\langle D \rangle$, $\langle F \rangle$ or $\langle G \rangle$, as discussed in section 2;
 - b) the existence of superpotential interactions which do not preserve the continuous $U(1)$ R -symmetry.

Ref. ²² showed that it was indeed possible to generate gluino masses by radiative corrections, through the interaction of gluinos with an “ad hoc” sector of what would be called now *vectorlike “messenger” quarks*, sensitive to the spontaneous breaking of the supersymmetry. But gluino masses radiatively generated along these lines generally tend to be rather small, unless one accepts to introduce, in some (often rather complicated) “hidden sector”, very large mass scales $\gg m_W$, so that radiatively-generated gluino masses could still end up to be of the order of several hundreds of GeV/c^2 ’s, as now experimentally required.

Fortunately gluino masses may also result directly from supergravity, as already observed in 1977⁵. Gravitational interactions require, within local supersymmetry, that the spin-2 graviton be associated with a spin-3/2 partner¹²,

the gravitino. Since the gravitino is the fermionic gauge particle of supersymmetry it must acquire a mass, $m_{3/2}$ ($= \kappa d/\sqrt{6} \approx d/m_{\text{Planck}}$), as soon as the local supersymmetry gets spontaneously broken. Since the gravitino is a self-conjugate Majorana fermion its mass breaks the continuous R -invariance which acts chirally on it (just as for the gluinos)⁵, forcing us to abandon the continuous $U(1)$ R -invariance, in favor of its discrete Z_2 subgroup generated by the R -parity transformation. We can no longer distinguish between the values $+1$ and -1 of the (*additive*) quantum number R ; but only between “ R -odd” particles (having $R = \pm 1$) and “ R -even” ones, i.e. between particles having R -parities $R_p = (-1)^R = -1$, and $+1$, respectively, as indicated in section 5 (cf. Table 4).

In particular, when the spin- $\frac{3}{2}$ gravitino mass term $m_{3/2}$ is introduced, the “left-handed sfermions” \tilde{f}_L , which carry $R = +1$, can mix with the right-handed ones \tilde{f}_R , which carry $R = -1$, through mixing terms having $\Delta R = \pm 2$, which may naturally (but not necessarily) be of order $m_{3/2} m_f$. Supergravity theories offer a natural framework in which to include direct gaugino Majorana mass terms

$$- \frac{i}{2} m_3 \bar{\tilde{G}}_a \tilde{G}_a - \frac{i}{2} m_2 \bar{\tilde{W}}_a \tilde{W}_a - \frac{i}{2} m_1 \bar{\tilde{B}} \tilde{B} , \quad (13)$$

which also correspond to $\Delta R = \pm 2$. The mass parameters m_3 , m_2 and m_1 , for the $SU(3) \times SU(2) \times U(1)$ gauginos, could naturally (but not necessarily) be of the same order as the gravitino mass $m_{3/2}$. This directly leads us to R -parity, defined as $R_p = (-1)^R$, as indicated in section 5, R -parity being $+1$ for ordinary particles, and -1 for their superpartners. Of course, once the continuous R -invariance is reduced to its discrete R -parity subgroup, a direct Higgs superfield mass term $-\mu H_1 H_2$ may be re-allowed in the superpotential, as done for example in the MSSM.

In general, irrespective of the supersymmetry-breaking mechanism considered, one normally expects superpartners not to be too heavy. Otherwise the corresponding new mass scale would tend to contaminate the electroweak scale, thereby *creating* a hierarchy problem in the Supersymmetric Standard Model. Superpartner masses are then normally expected to be naturally of the order of m_W , or at most in the $\sim \text{TeV}/c^2$ range.

8 Conclusions.

The Supersymmetric Standard Model (“minimal” or not), with its R -parity symmetry (absolutely conserved, or not), provided the basis for the experimental searches for the new superpartners and Higgs bosons. However, the “final” answer about how the supersymmetry should actually be broken is not known, and this concentrates most of the remaining uncertainties in the Supersymmetric Standard Model. Since the first searches for gluinos and photinos, selectrons and smuons, starting in the years 1978-1980, the experimental efforts have been pursued incessantly, for more than twenty years now, without giving us any direct evidence for the new supersymmetric particles yet. Supersymmetry as a symmetry of the real world, and the existence of the superpartners, and of the new additional Higgs bosons, still remain as physical hypotheses, that we would like to see confirmed experimentally, some day.

Many good reasons to work on supersymmetry, the Supersymmetric Standard Model and its various possible extensions have been widely discussed, dealing with supergravity, grand-unification (the $SU(3) \times SU(2) \times U(1)$ gauge couplings tend to unify at high energies, when their evolution is computed with the field content of the Supersymmetric Standard Model), extended supersymmetry, new spacetime dimensions, superstrings, “ M -theory”, But, after more than 20 years of experimental searches, we would certainly appreciate to start seeing the missing half of the SuperWorld being disclosed experimentally !

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